

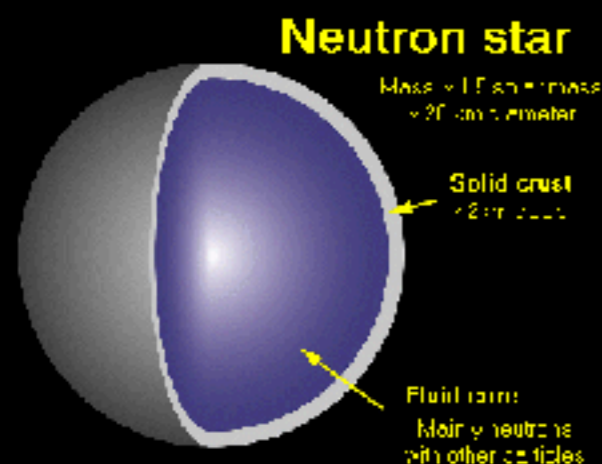
Neutron Star Mass and Radius Measurements: A New Era?

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CASS Seminar at UCSD

April 5, 2005

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Motivation

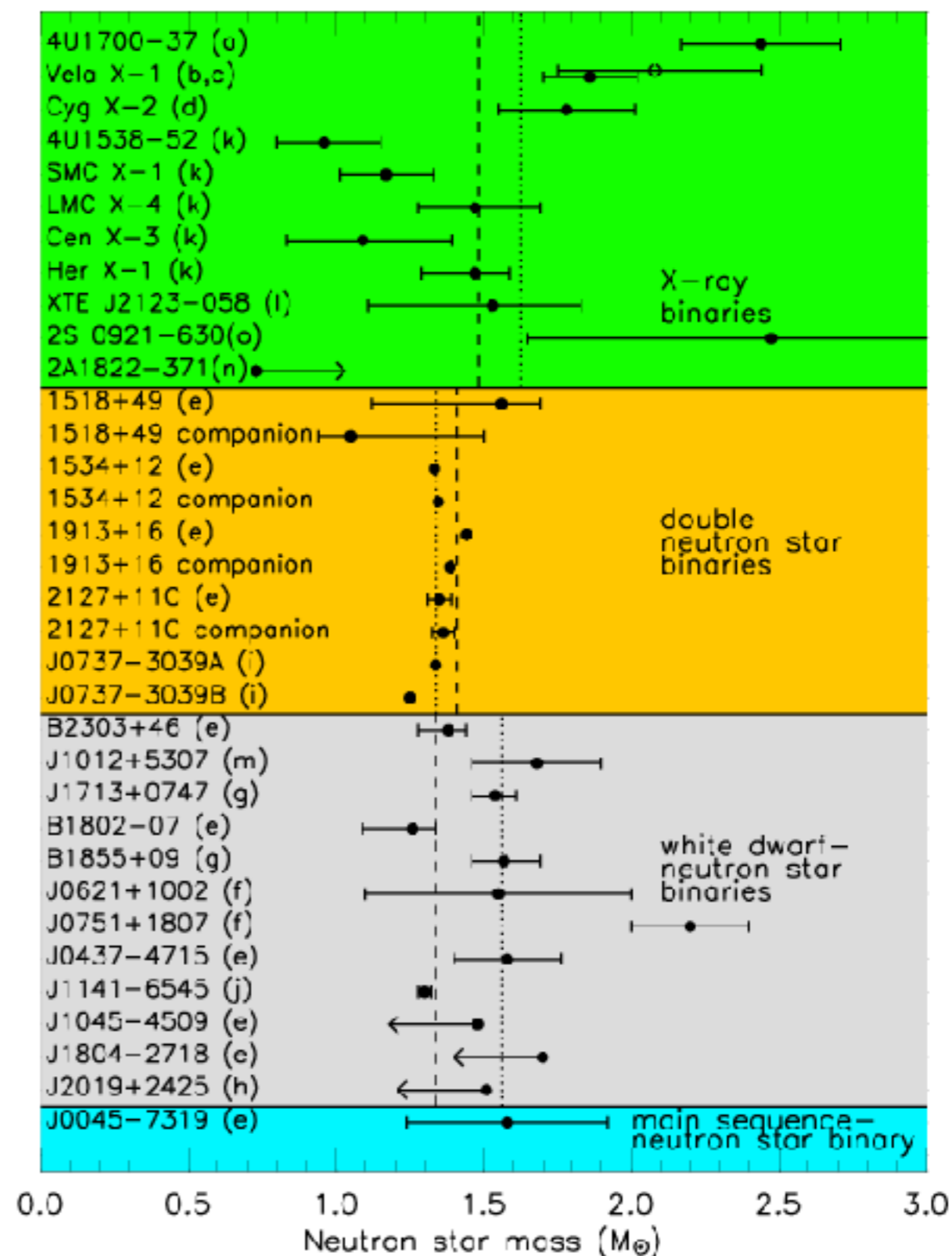
Question: Why are neutron stars interesting?

Answer: They are a unique window to the nature of dense matter.

- The presence of exotic matter (i.e. quarks, hyperons, Bose condensates) softens the equation of state - the pressure decreases more slowly as a function of increasing energy density
- The softening of the equation of state causes the mass and radius to decrease.
- We are on the brink of a *new era* where more is possible - neutron stars tell us something about the nuclear symmetry energy
- These are not the only observable implications of dense matter equation of state - neutrino signals from newly-born neutron stars and neutron star cooling

Mass measurements

- The most accurate mass measurements in NS-NS binaries are near 1.44 - the cluster of measurements is very suggestive.
- Recent measurements of neutron star masses are as large as 2 solar masses
- This does not yet rule out the presence of exotic matter, for example, neutron stars containing quarks may have similar masses
- A sufficiently small isolated neutron star mass might be a revolution! Supernovae can't create neutron stars smaller than one solar mass.
- It has not been proven that black holes formed in gravitational collapse have a mass larger than the neutron star maximum mass.



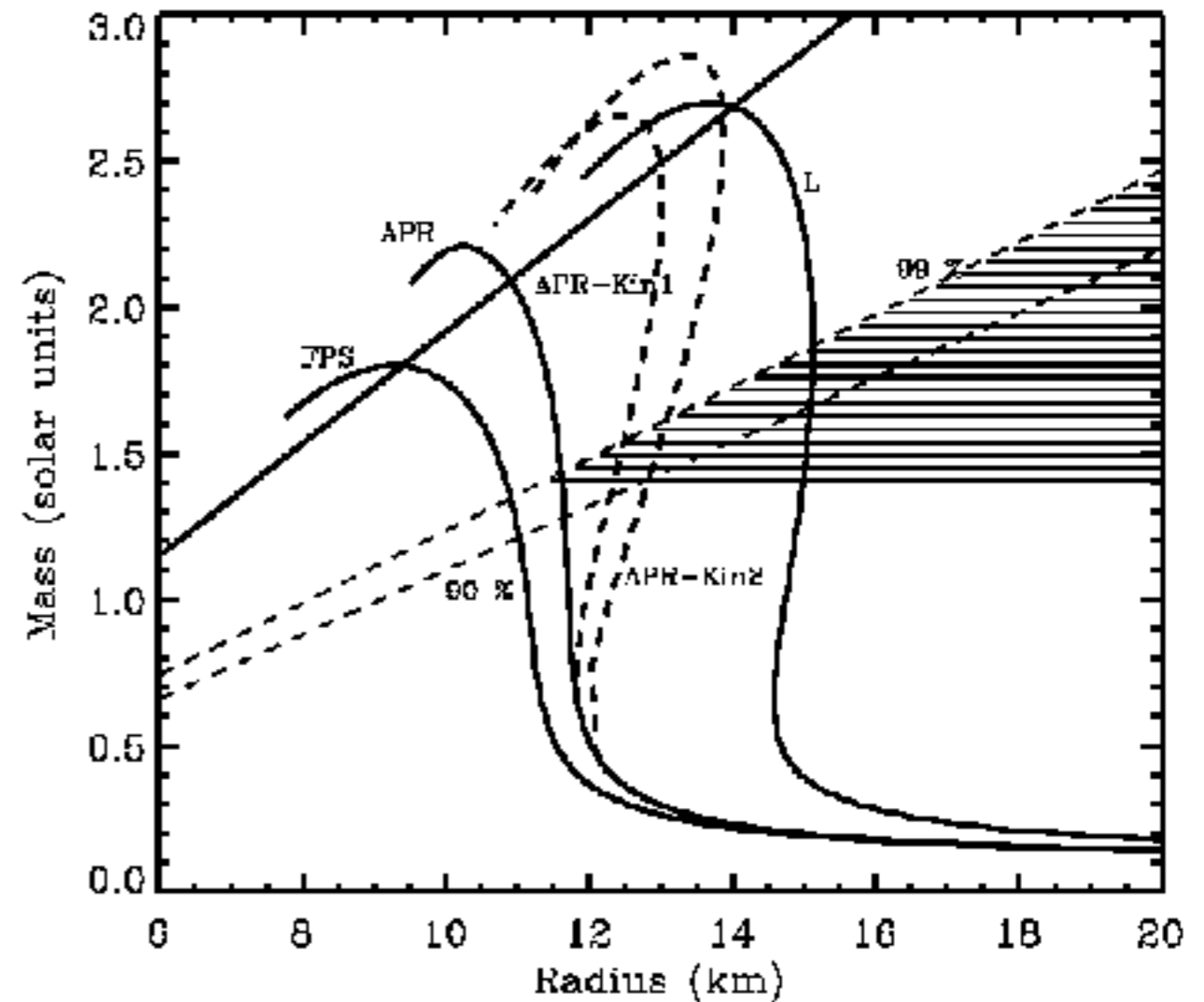
Taken from J.M. Lattimer and M. Prakash,
astro-ph/0411280

Radius Measurements

- Radius measurements are difficult: 1) its difficult to make accurate distance measurements, 2) they often involve modeling the neutron star atmosphere
- Recent measurements in globular clusters have been promising - 12.8 ± 0.4 km and 13.6 ± 0.3 km (Gendre, et. al. 2003)
- "Radius measurements" are difficult to interpret because they were calculated assuming a $1.4 M_{\odot}$ neutron star.
- The radius measurements are not yet constraining

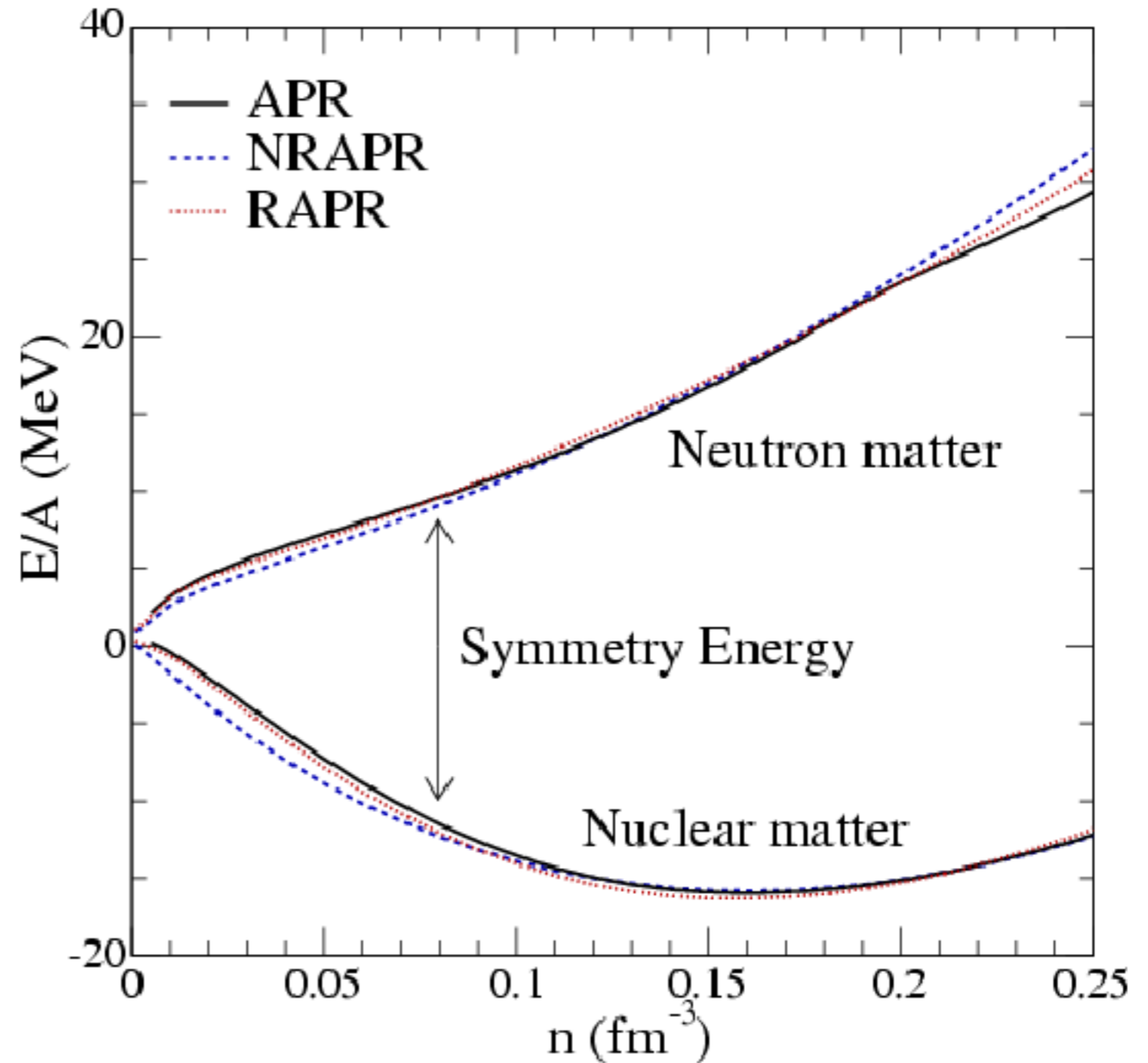
Other Observational Information

- Cottam, et. al. (2002) measured the redshift ($z=0.35$) in absorption lines in the spectra of X-ray bursts of XTE J1814-338. This constrains M/R and sets a lower limit on the central energy density.
- Pressure broadening of heavy-element lines due to the Stark effect may yield a measurement of M/R^2
- kHz QPOs have also been promising for measuring masses and radii: $M/R < 0.163$ (Nath, et. al. 2002) (suggests less exotic matter)
- More to come...
- There is a less exotic motivation for studying neutron star masses and radii, the symmetry energy!



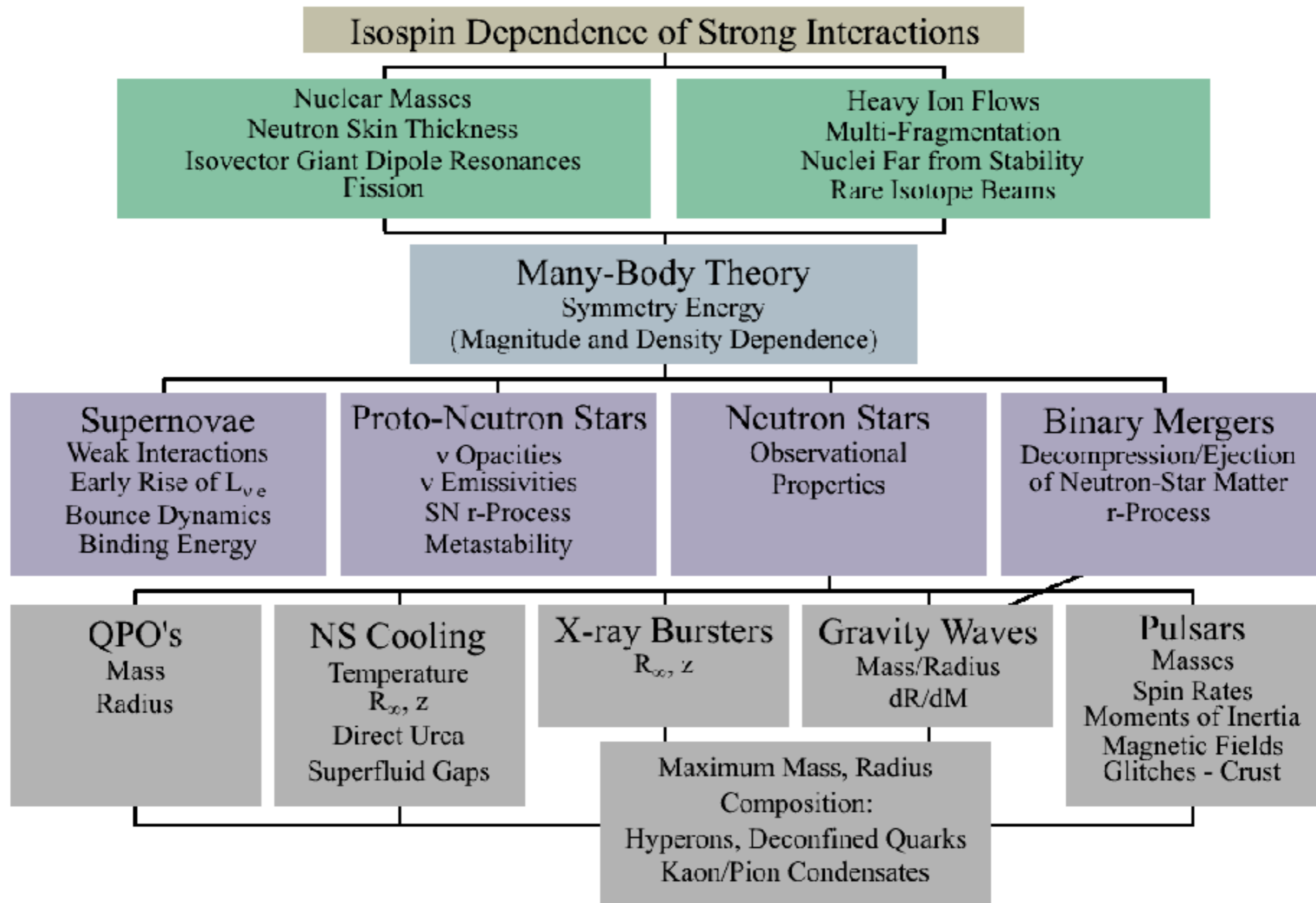
The Nuclear (A)symmetry Energy

- The symmetry energy is the size of the energy cost in QCD of creating an asymmetry between the number of neutrons and protons
- Note that the pressure (at zero T) is related to the derivative of the energy per baryon (E/A)
- Of concern is the magnitude of the symmetry energy and its density dependence



Taken from A.S., M. Prakash, J.M. Lattimer,
and P.J. Ellis, Phys. Rep. (2005) in press.

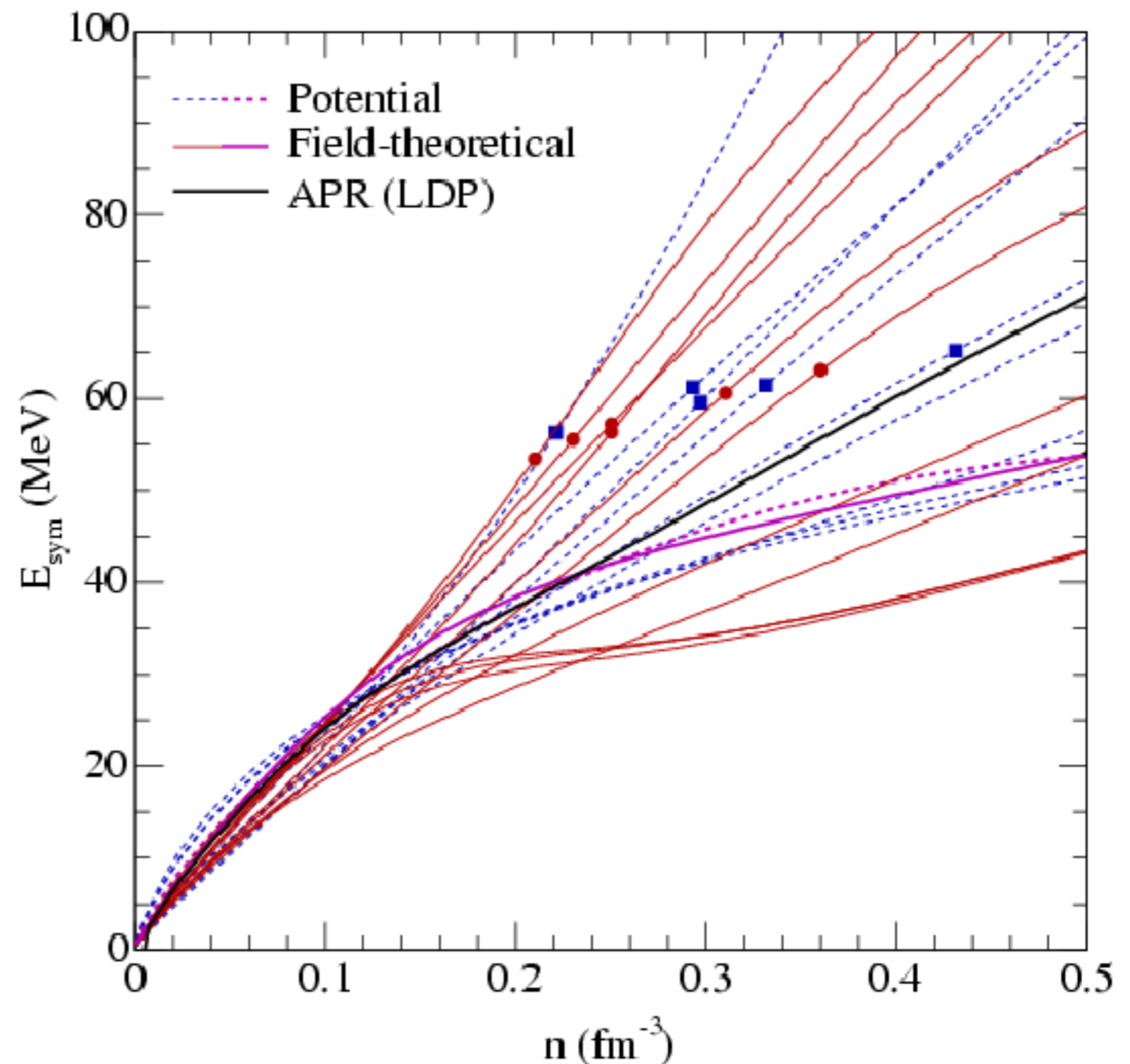
The Influence of the Nuclear Symmetry Energy



Taken from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, Phys. Rep. (2005) in press.

The Nuclear Symmetry Energy

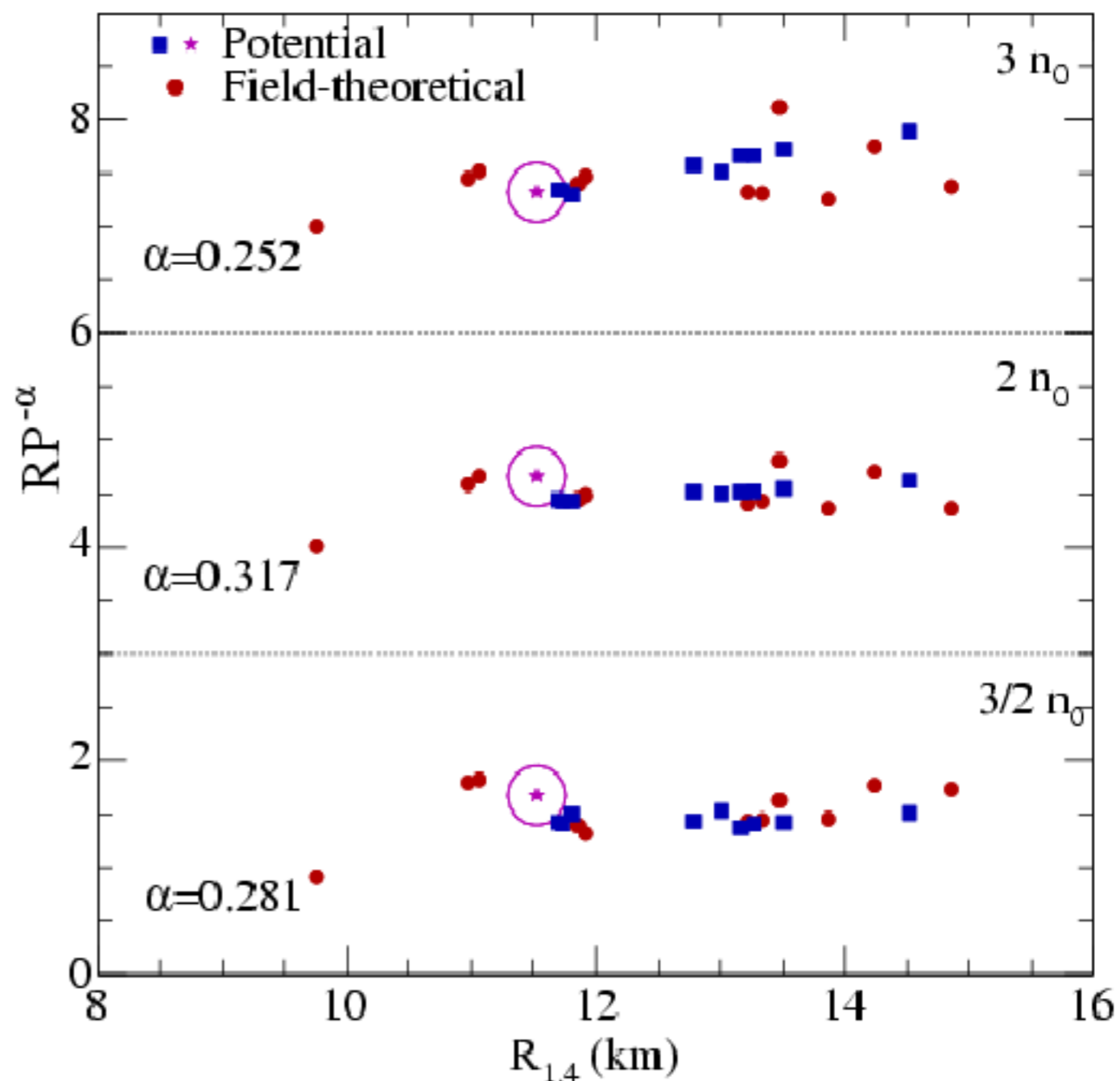
- There is considerable variation among models, both relativistic and non-relativistic
- Relativistic models = Extensions of the Walecka model to include higher order interactions between the isoscalar and isovector mesons
- Non-relativistic models = Skyrme Hamiltonian
- APR = Akmal, et. al. - Ab-initio Monte Carlo calculations of nuclear and neutron matter



Taken from A.S., M. Prakash, J.M. Lattimer,
and P.J. Ellis, Phys. Rep. (2005) in press.

Lattimer-Prakash correlation

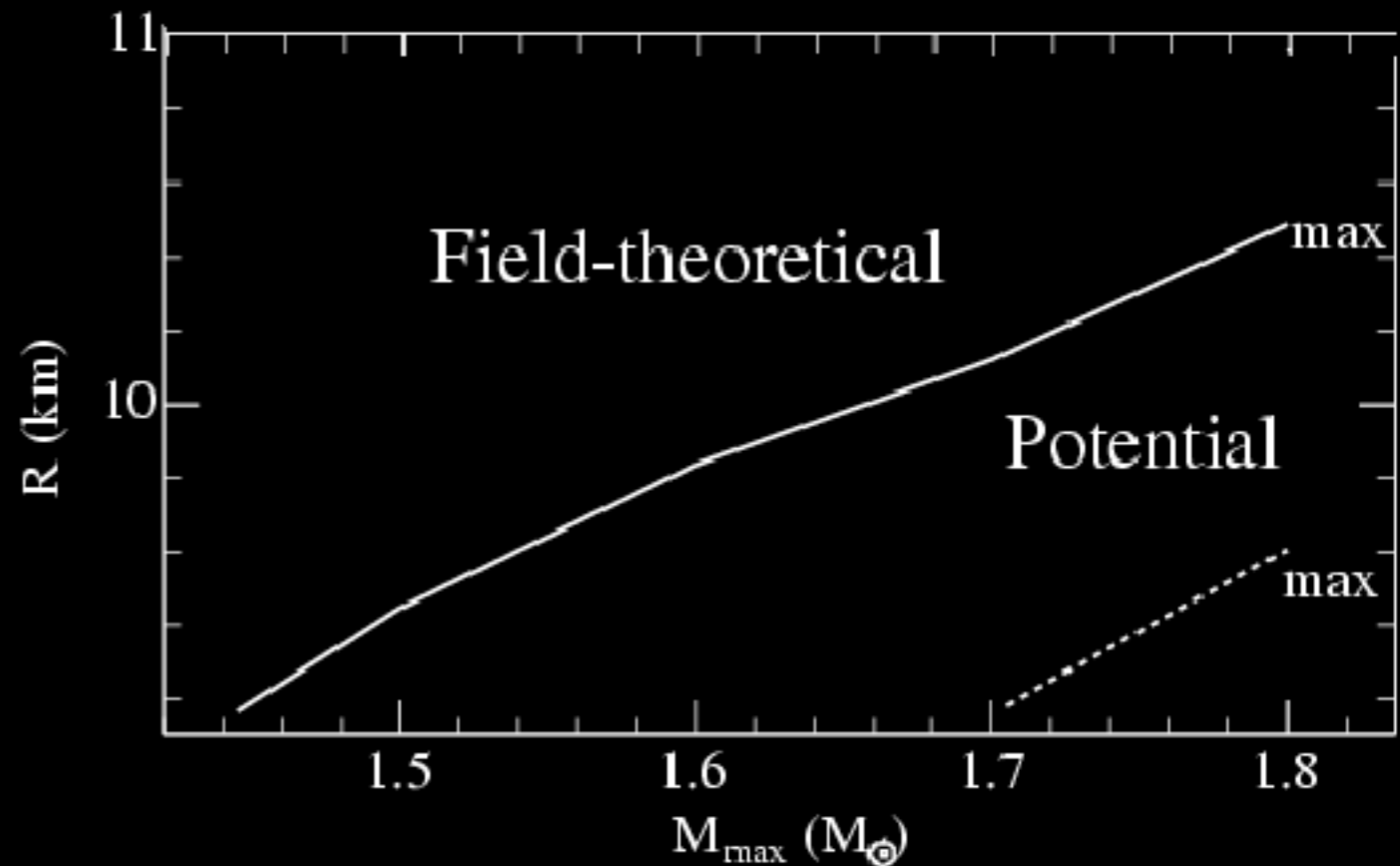
- Analytical solutions of the Tolman-Oppenheimer-Volkov equations suggest that $RP^{-\alpha} \sim \text{constant}$
- Therefore the radius is correlated with the pressure at densities somewhat larger than nuclear matter densities
- Thus neutron star radii are determined, in large part, by the symmetry energy



Taken from A.S., M. Prakash, J.M. Lattimer,
and P.J. Ellis, Phys. Rep. (2005) in press.

Small Neutron Star Radii

- What is the smallest possible radius for a neutron star which doesn't contain exotic components?
- Largest accurate mass measurements used to be 1.44 solar masses, now they may be as large as 2.0!
- Neutron star radius measurements are becoming available in globular clusters, where distance and age is easier to determine.

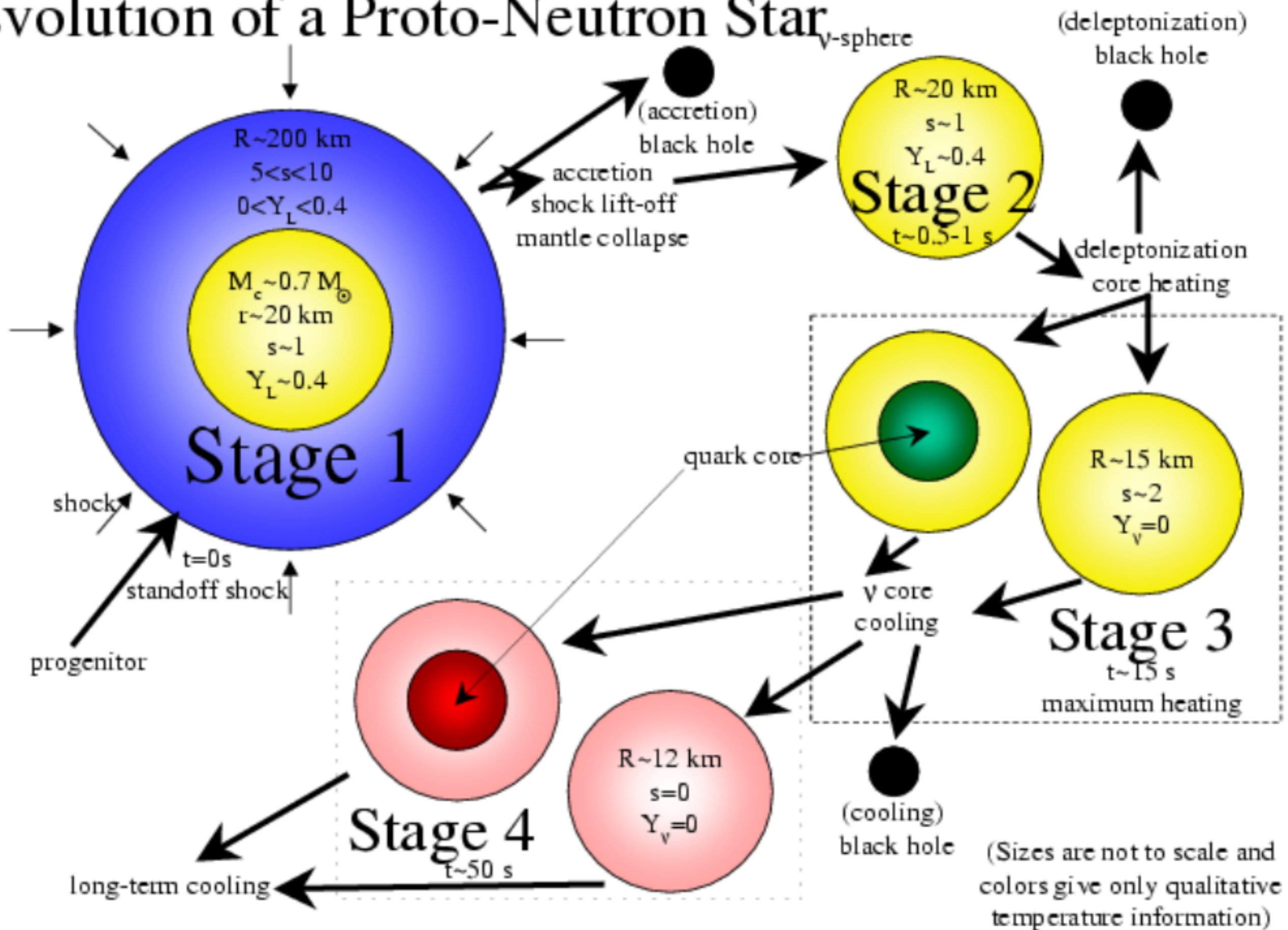


Adapted from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, Phys. Rep. (2005) in press.



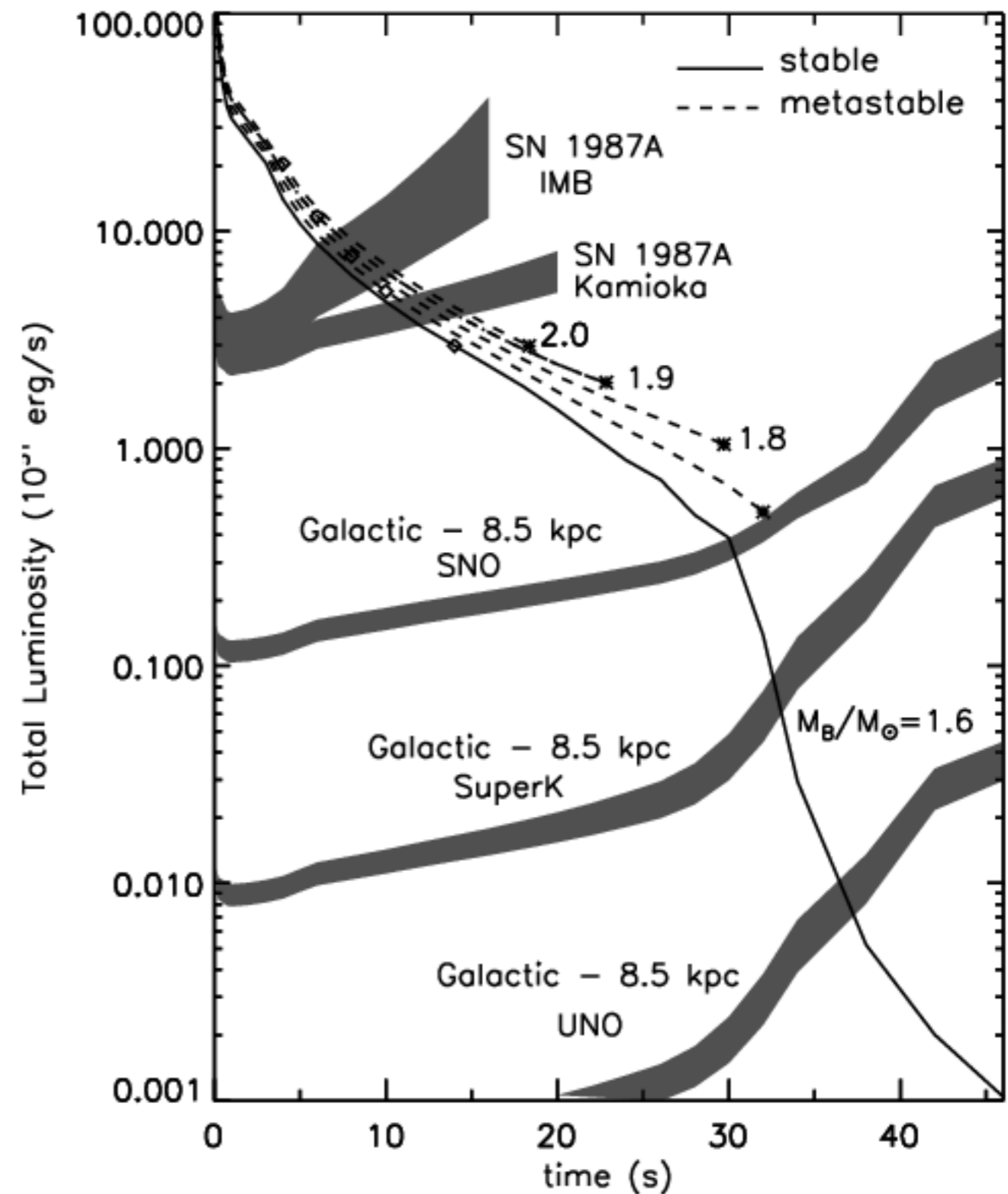
Globular cluster M13

Evolution of a Proto-Neutron Star



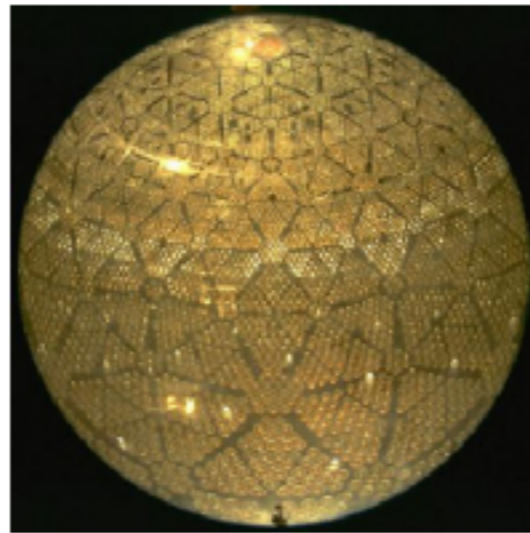
Proto-Neutron Star Neutrino Signal

- 20 neutrinos from SN1987A
- Thousands of neutrinos from a galactic supernova in present-day neutrino detectors (not to mention future detectors which may be larger)
- Galactic supernova rate is about 1 every 30 years.

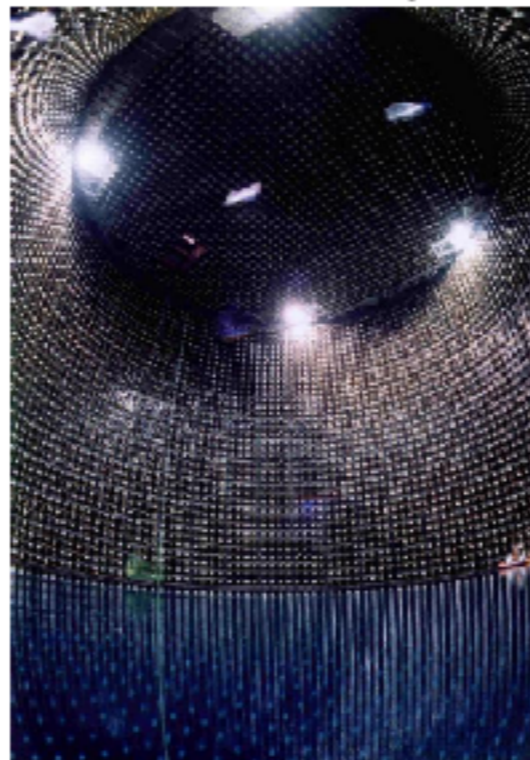


Proto-Neutron Star Metastability

- Metastability - Neutron stars, if they contain an exotic component, may collapse to black holes only after the neutrinos have left
- This provides a way to discern the content of the interior
- The first study of metastability in neutron stars giving an observable prediction - Phys. Rev. Focus.

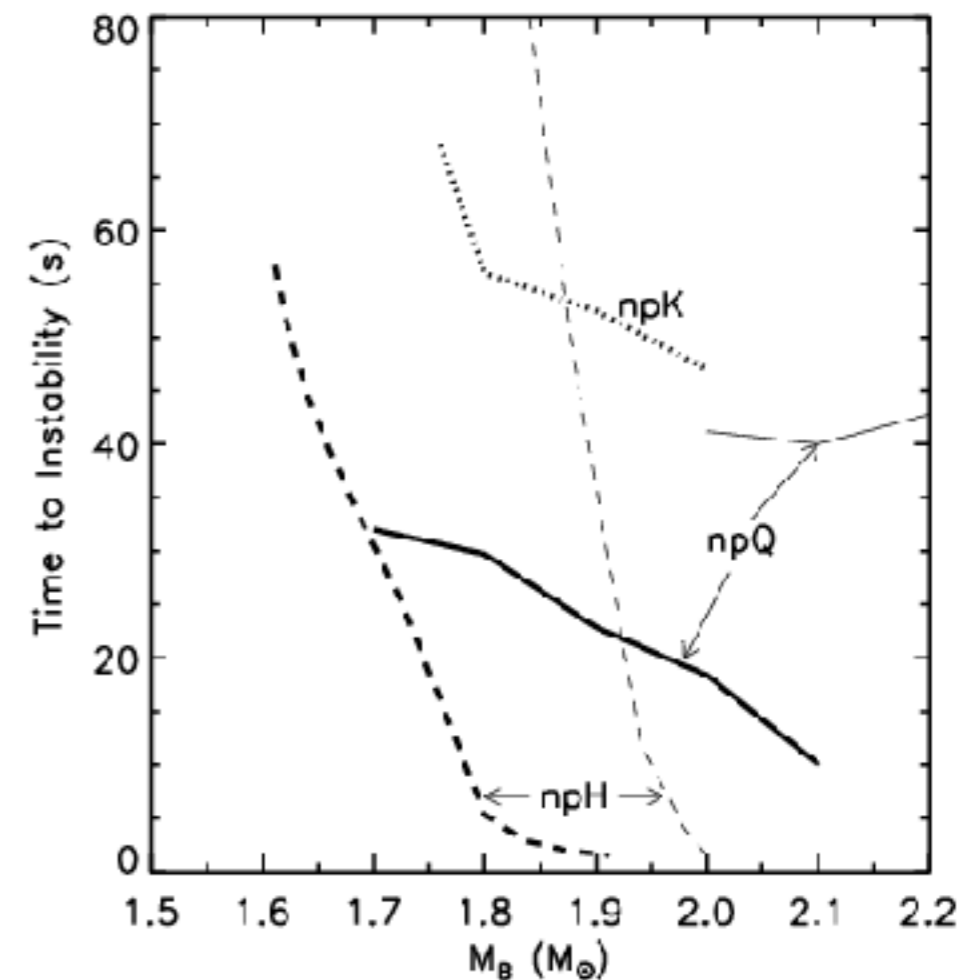


Solar Neutrino Observatory



Super-Kamiokande

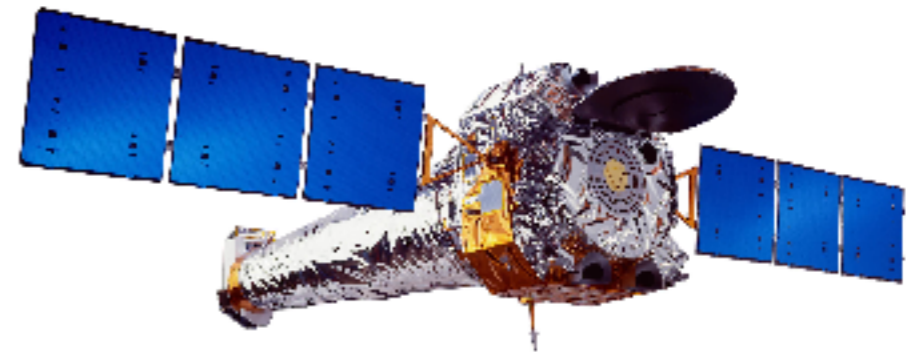
More in the future?



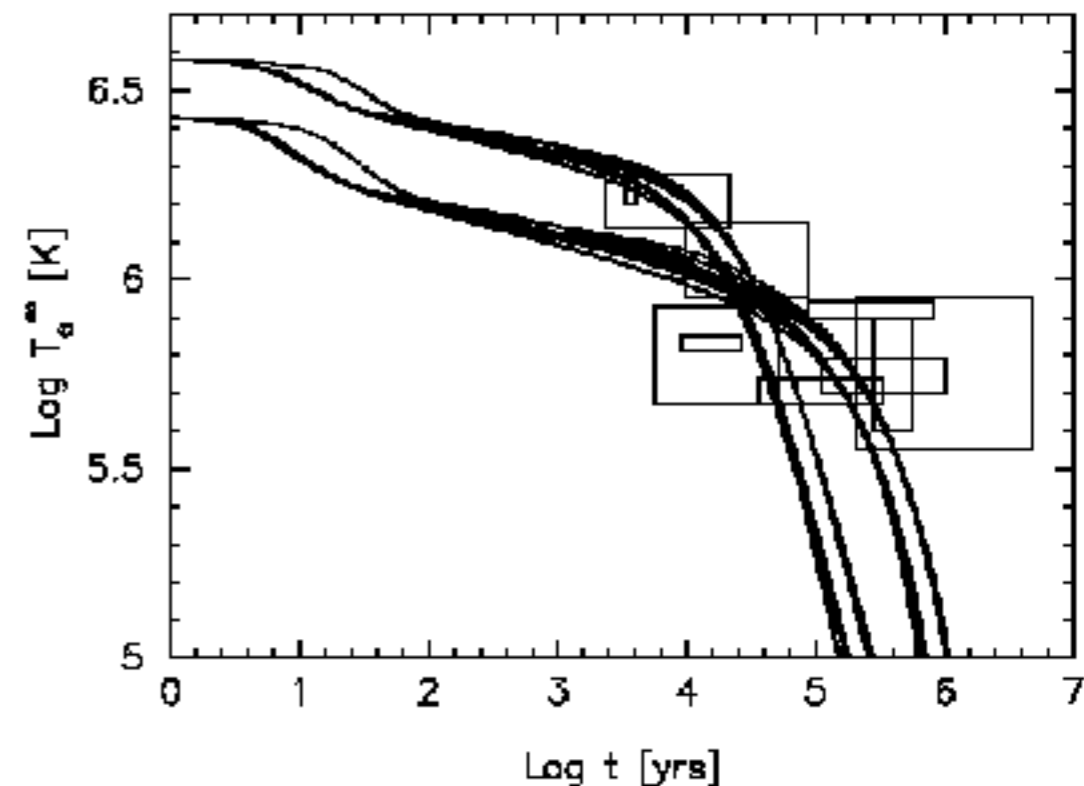
Taken from J. Pons, A. S., M. Prakash,
and J.M. Lattimer,
Phys. Rev. Lett. 86 (2001) 5223.

Neutron Star Cooling

- Neutron star cooling is observable in X-rays for millions of years
- Age can be derived from SN associations, spin-down age
- Using the equation of state and neutrino emissivities - calculate a cooling curve
- Demonstrated that exotic forms of matter are hidden because their effect is identical to other effects. [PRL 85 (2000) 2048]
- Recent observations suggest that a few neutron stars are either too cool or too warm without "non-standard" physics [2004]



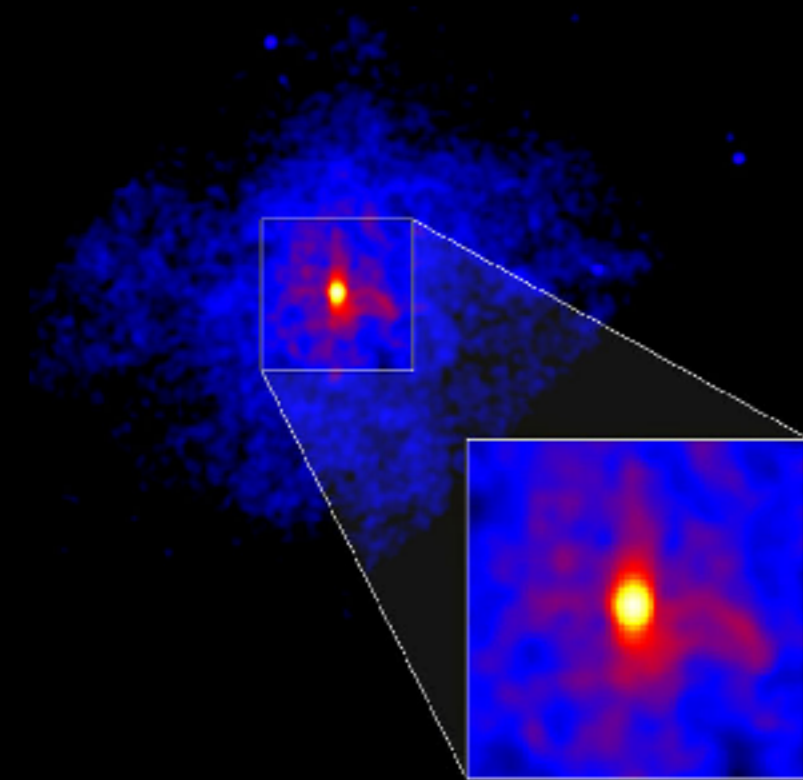
X-ray (Chandra)



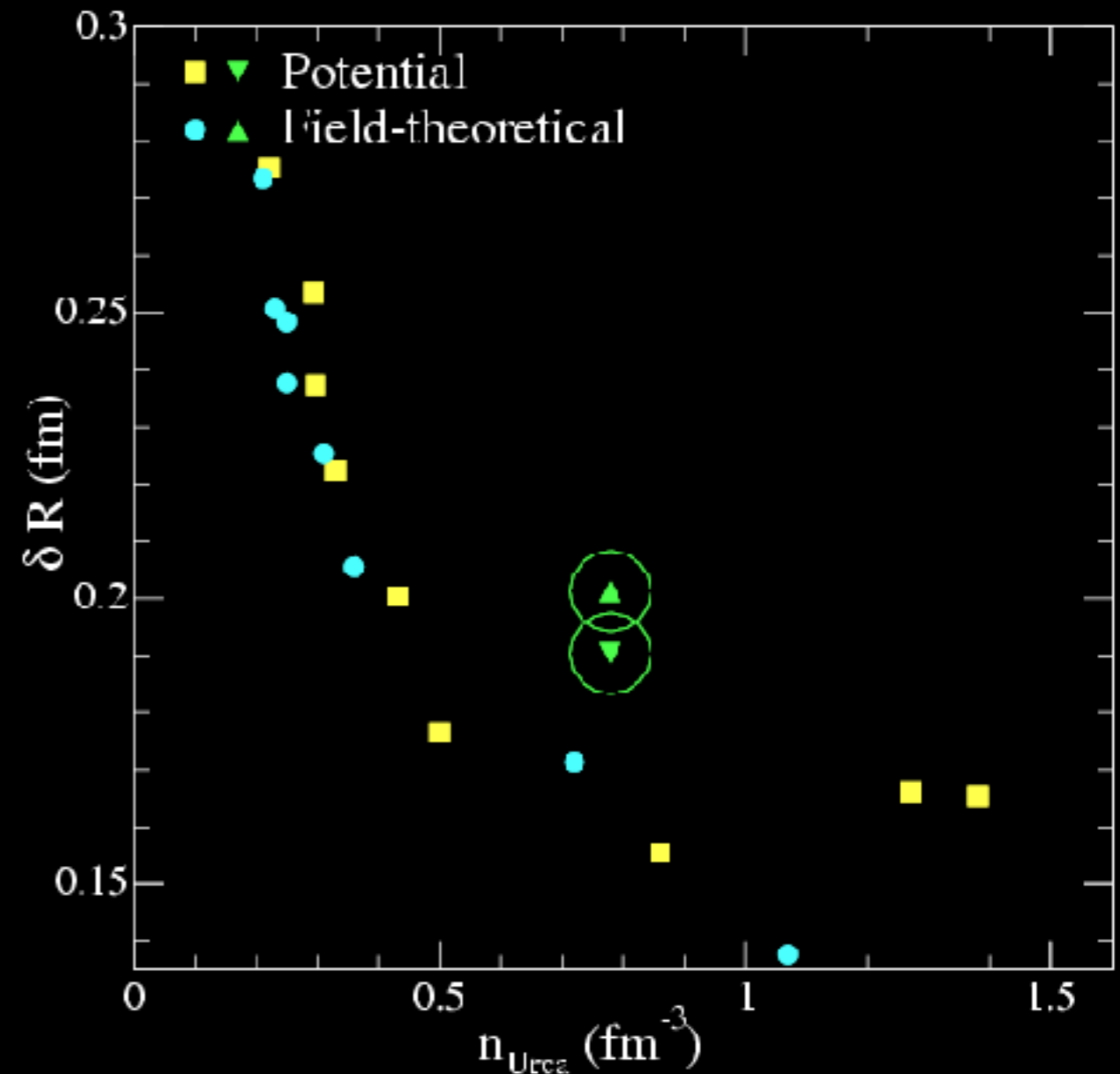
Taken from D. Page, J.M. Lattimer,
M. Prakash, and A. S., Astrophys. J.
Supp. 155 (2004) 623.

Neutron star cooling

- Neutron star cooling is strongly affected by the presence of direct URCA
- The critical density for direct URCA is controlled by the symmetry energy



Neutron star 3C58



Taken from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, Phys. Rep. (2005) in press.

Summary

- Neutron star masses and radii will provide information about the nature of dense matter
 - Is exotic matter present?
 - What is the magnitude and density dependence of the nuclear symmetry energy?
- There are several other observables that may prove useful
 - The proto-neutron star neutrino signal
 - Neutron star cooling data
- With regard to the symmetry energy this is less than half of the story!
 - The r-process!
 - Nuclear structure and heavy-ion collisions